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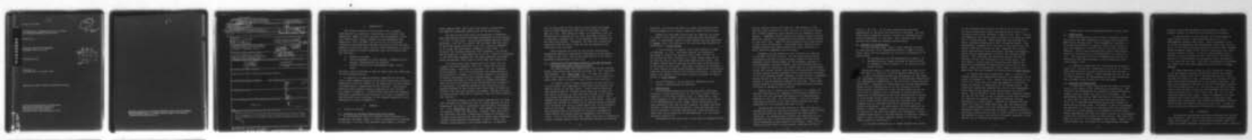

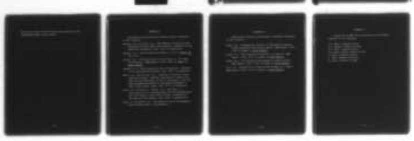

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COOPERATIVE STUDIES OF SOLAR ACTIVITY
AND CHROMOSPHERIC STRUCTURE

Harold Zirin

California Institute of Technology
Pasadena, California 91125

7 December 1976

Final Report
1 October 1975 - 30 October 1976

AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AFB, MASSACHUSETTS 01731

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFGL-TR-77-0105	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) COOPERATIVE STUDIES OF SOLAR ACTIVITY AND CHROMOSPHERIC STRUCTURE.		5. TYPE OF REPORT & PERIOD COVERED Final Report. 1 Oct 1975 - 30 Oct 1976
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Harold Zirin		8. CONTRACT OR GRANT NUMBER(s) F19628-76-C-0055 new (955)
9. PERFORMING ORGANIZATION NAME AND ADDRESS California Institute of Technology Pasadena, California 91125		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62101F 76490616
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Geophysics Laboratory Hanscom AFB, Massachusetts 01731 Monitor/Simon P. Worden/PH		12. REPORT DATE 7 Dec 1976
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 15p.		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

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18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Flares, Sun

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Observations were carried out and analyzed on the physics of solar flares, active phenomena in quiet regions: such as ephemeral active regions, macrospicules and spicules, and Coronal holes and the chromosphere under coronal holes.

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I. INTRODUCTION

The general purpose of this contract was to support observations and analyses of observations at Big Bear Solar Observatory (BBSO) of solar activity and chromospheric structure which were of mutual interest to both Sacramento Peak Observatory (SPO) and BBSO, and in this way to facilitate interaction and cooperation between scientists at SPO and BBSO engaged in studies of solar activity and chromospheric structure. The main areas of research supported under this contract were the following:

1. Physics of flares.
2. Active phenomena in quiet regions: ephemeral active regions, macrospicules and spicules.
3. Coronal holes and the chromosphere under coronal holes.

The major results obtained in each of these areas are summarized in the following section.

In addition to research directly supported by this contract, other research projects in the above areas were indirectly supported through the funding of the observatory and the funding of observations in these areas by the contract. Publications resulting from research directly supported by this contract are listed in Appendix A. Publications resulting from research indirectly supported by this contract are listed in Appendix B. The scientists who contributed to the research reported in this document are listed in Appendix C.

II. RESULTS

A. Physics of Flares

1. Isotropy of the Hard X-Rays from Solar Flares

In collaboration with D.W. Datlowe of the University of California, San Diego (UCSD), R. Moore investigated the isotropy of the hard ($\gtrsim 10$ keV) X-ray emission from flares in a study which combined UCSD OSO-7 hard X-ray spectral observations with BBSO Hα filtergram observations of the same flares.

The hard X-rays from flares are produced by bremsstrahlung from electrons which have been accelerated to high energies ($\gtrsim 10$ keV) in the flare. For plausible ambient particle number densities ($\lesssim 10^{11}$ cm^{-3}) in flares, the collision mean free path of such high energy electrons is $\gtrsim 10^{9}$ cm, which is comparable to or longer than the overall dimension of the flare. In contrast, for plausible magnetic field strengths ($\gtrsim 10$ gauss), the gyroradius of 10 keV electrons is $\lesssim 10^{2}$cm. From such estimates it has often been supposed that the hard electrons are beamed along the magnetic field lines on which they are accelerated.

The hard X-rays from flares can be fit fairly well by a power-law energy spectrum, $F(E) \propto E^{-\gamma}$, where the so-called hardness index γ specifies the flatness, i.e. the hardness, of the spectrum. For > 10 keV electrons, the bremstrahlung in each collision is beamed in the forward direction, the degree of beaming increasing with the electron energy. Consequently, if the hard electrons in solar flares are themselves beamed, then the hard X-ray emission from flares should be anisotropic. In particular, an observed center-to-limb variation in the average hardness of hard X-rays from flares would be empirical evidence that the hard electrons are beamed, whereas no center-to-limb variation would be an indication that the hard electrons are isotropic.

The energy spectra of hard X-rays observed with the UCSD OSO-7 detector and identified with Hα flares reported in Solar Geophysical Data show a significant limb softening (Datlowe et al.: 1974, Solar Phys. 39, 155). This appears to be evidence for beaming of the hard electrons. However, Moore found that the UCSD data also show a correlation between the hardness of the hard X-ray spectrum and the overall length scale (measured on BBSO high-resolution filtergrams) of the Hα flare, with smaller flares tending to have harder spectra. In addition, the low-resolution Hα flare patrols which report the flares given in Solar-Geophysical Data tend to miss small flares near the limb. This selection effect in combination with the correlation of hardness with Hα flare smallness accounts for a large part, possibly all, of the apparent limb softening of the hard X-ray bursts. Therefore, the UCSD OSO-7 bursts are compatible with the hard X-rays and the corresponding hard electrons being isotropic.

Moore reported this work at the United States-Japan Cooperative Seminar on High-Energy Phenomena in Solar Flares, in Tokyo in May, 1976, and at the 148th Meeting of the AAS in Haverford, Pennsylvania in June 1976.

2. Channeling of High-Energy Electrons and Mass Ejections by Large-Scale Solar Magnetic Fields.

An unusual number and proportion of Type III-RS (reverse slope) radio bursts were observed on August 12, 1975 (Tarnstrom and Zehntner: 1975, Nature 258, 693). On that day, some 30 Type III-RS bursts were observed, whereas in the previous five years there were an average of only 39 such events annually.

B. LaBonte found a simple explanation for the August 12, 1975 RS bursts from comparison of the radio observations with BBSO Hα movies of the same flares. These flares occurred at the preceding edge of a sunspot group which was at about 45° west solar longitude, so that the line of sight to the flares lay through the enhanced corona above the spot group. This suggests the following explanation for the RS bursts. The radio bursts were emitted as U bursts by an electron stream traveling from the flare site along a closed field line to the following part of the group. The emission at the plasma frequency on the preceding side of the field line could not propagate to earth through the coronal density enhancement over the spot group. Only on the following side, where there was no intervening region of higher density could the emitted radiation be observed.

Therefore, the bursts were seen only where the electrons were moving downward in the corona, producing reverse slope bursts.

LaBonte has confirmed this picture by computing ray paths in a model of the active region constructed from the observations. A preliminary report of these results has been published in Nature, and a full account of the work has been accepted for publication in Solar Physics.

H. Zirin studied an unusual surge event observed at BBSO on September 17, 1971. The surge material was apparently channeled by large-scale magnetic field lines to return to the surface and form a filament in a quiet region some 200,000 km from the site of the flare which threw out the surge. The filament lasted about 30 minutes and then rose up and returned to the source of the surge. This event indicates the existence in quiet regions of semi-stable magnetic traps which are potential sites for filament formation and filament eruptions. A detailed account and analysis of this event has been accepted for publication in Solar Physics.

B. Active Phenomena in Quiet Regions: Ephemeral Active Regions, Macrospicules and Spicules

1. Observations

EUV spectroheliograms from Skylab show small surge-like eruptions, called macrospicules, on the limb in quiet regions, especially in the polar coronal holes. R. Moore and F. Tang (1975, B.A.A.S. 7, 423) found that eruptive events very similar to EUV macrospicules in size, shape, motion and duration are also observed on the limb in quiet regions, including the polar regions, on BBSO full-disk Hα movies. From the similarity of the Hα eruptions to the EUV macrospicules, Moore and Tang proposed that the Hα events are Hα macrospicules, i.e. EUV macrospicules viewed in Hα .

Macrospicules are flare-like in that they are sudden eruptive events, usually having rise times of a few minutes or less. The only known locations of flare activity in the polar regions and in other apparently quiet regions are the ephemeral active regions. (Ephemeral active regions are bipolar magnetic regions which are smaller than supergranules and usually have lifetimes of less than a day. They are the so-called X-ray bright points in soft X-ray filtergrams.) From these facts, Moore and Tang further proposed that macrospicules are surges produced by small flares in ephemeral active regions.

Ephemeral active regions are very difficult to identify on the BBSO full-disk Hα films. On the higher-resolution Hα filtergrams from the 10-inch telescope (field of view $\approx 5' \times 7'$) ephemeral active regions appear as the brightest features in the chromospheric emission network, and can be identified with a fair degree of certainty even without the aid of magnetograms. During the contract period, many days of high-resolution coverage of quiet regions showing ephemeral active regions were obtained. We now have observed several examples of flare events in ephemeral active regions on the disk which produce small eruptions very similar to the Hα eruptions observed on the limb. These observations support the hypothesis that macrospicules are generated by flares in ephemeral active regions.

Another way of testing this hypothesis is to compare the latitude distribution of ephemeral active regions observed on the disk with the latitude distribution of Hα macrospicules observed on the limb. For this purpose, a full day of high-resolution Hα movies of the limb in quiet regions has been completed for all latitudes from pole to pole.

Macrospicules were named such due to their similarity to ordinary Hα spicules, and this similarity suggests that spicules and macrospicules are both generated by the same physical mechanism. Our observational evidence that macrospicules are generated by small flares therefore suggests that spicules may be generated by even smaller flare events. Using a motor-driven Hα filter which is continuously tuned back and forth from Hα + 1Å to Hα - 1Å, we have obtained some excellent observations of the birth and evolution of spicules. We have found several examples in which a spicule is accompanied by a tiny Hα brightening at its base. This indicates that some spicules may indeed be miniature macrospicules.

2. Analysis of Observations

As was discussed above, from a study (carried out prior to this contract) of Hα macrospicule events on BBSO full-disk films, Moore and Tang proposed the following interpretation of these events.

1. Hα macrospicules are EUV macrospicules viewed in Hα.
2. Macrospicules are surges produced by flare activity in ephemeral active regions (i.e. by flares in X-ray bright points).

During the period of this contract, Moore and Tang collaborated with J.D. Bohlin of the Naval Research Laboratory and with L. Golub of American Science and Engineering to test these two hypotheses by comparison of BBSO Hα macrospicule observations with simultaneous observations in the EUV and in X-rays obtained from Skylab. Comparison of simultaneous Hα and EUV observations showed that Hα macrospicules do in fact coincide with EUV macrospicules, although most ($\sim$90%) EUV macrospicules are too faint in Hα to appear on Hα filtergrams of normal exposure. Comparison of simultaneous Hα and X-ray observations of flares in X-ray bright points located on the limb showed that flares in X-ray bright points often produce Hα macrospicules. This suggests that all macrospicules may be generated by still smaller microflares. (As noted above, our high-resolution Hα movies of flares in ephemeral active regions on the disk and of spicules on the disk also support this suggestion.) Moore reported these results at the AAS Meeting in Haverford, Pennsylvania in June, 1976 and a complete account of the work is nearly ready for publication.

In a related investigation, K. Marsh carried out a study of the lifetimes and evolution of fibrils in an active region for which exceptionally good high-resolution Hα and Ca II K filtergram movies were obtained at BBSO in July, 1973. Fibrils are apparently the active region analogue of the spicules which occur in quiet regions. Marsh found that the lifetime of a fibril increases monotonically with its maximum length. This relationship, together with the form of the variation of the fibril length as a function of time, suggests that fibrils result from material being impulsively injected into magnetic field lines at approximately 30 km/sec and returning under gravity. The lifetimes and lengths of fibrils are then a function of only the inclination of the field lines. With this result, we again have an indication that fibrils and spicules are generated by sudden flare-like events at their bases. Marsh has reported his fibril study in detail in a paper which has been accepted for publication in Solar Physics.

B. LaBonte has nearly completed a study of a series of intense flares which apparently occurred in an ephemeral active region on November 15, 1974. These flares were located on the limb at 78° south solar latitude and appeared as impulsive bursts of emission on BBSO helium D3 filtergram movies. The flares were apparently embedded well down in the chromosphere since they did not appear on our simultaneous full-disk Hα movie. The low height of these flares, their impulsive character and the fact that D3 was in emission rather than absorption all indicate the presence of intense nonthermal electron acceleration in these flares. LaBonte has computed detailed models for these D3 flares which show that the observations are in good agreement with the chromosphere being heated by impulsive bursts of non-thermal electrons. LaBonte presented preliminary results of his work on these flares at the Haverford AAS meeting in June, 1976 and he is currently preparing a final account of his findings for publication.

C. Coronal Holes and the Chromosphere Under Coronal Holes

1. Observations

Under the supervision of K. Marsh, a helium D3 coronal hole patrol has been conducted on a routine daily basis at BBSO during the past year. The chromospheric limb band in D3 is greatly reduced in intensity under coronal holes, so that the presence of a coronal hole on the limb is readily observed. Visual limb scans typically enable the position angle of a hole boundary to be determined to an accuracy of $\pm$ 3°. The locations of the hole boundaries on each day of observation have been published in Solar-Geophysical Data since January, 1976.

In addition to observing the limb positions of coronal holes in D3, several-day sequences of Hα and Ca II K filtergram observations of the polar regions were also obtained during the contract period. These observations will be used to study changes in the chromosphere across hole boundaries, and to measure solar rotation at high latitudes.

2. Analyses of Observations

R. Moore and D. Rabin investigated the effect of coronal holes on the height of the underlying Hα chromosphere. The height of the chromosphere was measured by making microdensitometer tracings across the limb on Hα filtergrams. The measurements were made on BBSO full-disk Hα filtergrams taken in June, 1973 on days for which there were NRL full-disk He II 304 Å spectroheliograms from Skylab which showed the positions of coronal holes. The height of the Hα chromosphere was measured as a function of latitude across hole boundaries as well as in quiet regions in the absence of coronal holes. These measurements show that the steady increase of chromospheric height with latitude followed in quiet regions away from holes does not occur in the chromosphere under holes. There is also weak evidence that the height of the chromosphere increases slightly across hole boundaries from outside to inside. A complete account of this work is currently being written.

In another study of the structure of the chromosphere under coronal holes, K. Marsh has analyzed the Ca II K chromospheric network under holes. Using microdensitometry of K-line filtergrams of the chromosphere under known coronal holes, he has found that there are significantly fewer enhanced network elements under coronal holes in comparison with quiet regions outside of holes. It is not clear whether this is an effect of the overlying coronal hole back on the chromosphere or a direct effect of the magnetic field distribution in the region of the hole. This work is reported and discussed in a paper which has been accepted for publication in *Solar Physics*.

W. Adams completed a study of the differential rotation of the photospheric magnetic fields surrounding the largest equatorial coronal hole (CH 1) observed from Skylab. Using the BBSO full-disk Hα films, he measured the positions of filaments and plages surrounding CH 1 for several rotations. The resulting differential rotation curve was considerably flatter than the standard curve (i.e. the rotation rate fell off more slowly with latitude) and was in good agreement with the curve found by Timothy et al. (1975, Solar Phys. 42, 135) for the overlying coronal hole itself. Thus, in agreement with other evidence that coronal holes are formed by large-scale open magnetic field structures, the underlying photospheric magnetic field pattern was found to rotate with the hole. A report on this work has been accepted for publication in *Solar Physics*.

III. CONCLUSION

The preceding paragraphs show that significant new results were obtained in each of the three areas of research supported under this contract. Many of the results provide a basis and guide for further research, particularly for the study of spicules and for the study of the structure and rotation of the chromosphere under coronal holes.

APPENDIX A

Publications resulting from research directly supported by this contract.

Datlowe, D.W. and Moore, R.L., "The Absence of Center-to-Limb Variations in Solar Hard X-Ray Emission", presented at the Haverford AAS meeting, June, 1976; in preparation

LaBonte, B.J., "Solar Activity on August 12, 1975", Nature 261, 525, 1976.

LaBonte, B.J., "Hα Observations of the August 12, 1975 Type III-RS Bursts", BBSO Report # 0155, 1976; to appear in Solar Physics.

LaBonte, B.J., "Polar Flares with He I D3 Emission", presented at the Haverford AAS meeting, June, 1976; in preparation

Moore, R.L., and Datlowe, D.W., "Isotropy of the Hard X-Rays from Solar Flares: Evidence from Spectral Observations from the UCSD Experiment on OSO-7", presented at the U.S.-Japan Cooperative Seminar on High Energy Phenomena in Solar Flares, Tokyo, Japan, May, 1976; in preparation.

Moore, R.L, and Tang, F., Bohlin, J.D., and Golub, L., Identification of Hα Macrospicules with EUV Macrospicules and with Flares in X-Ray Bright Points", presented at the Haverford AAS meeting, June, 1976; in preparation.

Rabin, D. and Moore, R.L., "The Height of the Hα Chromosphere Under Coronal Holes", in preparation.

APPENDIX B

Publications resulting from research indirectly supported by this contract

Adams, W.M., "Differential Rotation of Photospheric Magnetic Fields Associated with Coronal Holes", BBSO Report # 0153, 1976, to appear in Solar Physics.

Marsh, K.A., "The Lifetime and Evolution of Fibrils", BBSO Report # 0156, 1976; to appear in Solar Physics.

Marsh, K.A., "The Calcium K-Line Network in Coronal Holes", BBSO Report # 0157, 1976; to appear in Solar Physics.

Zirin, H., "Production of a Short-Lived Filament by a Surge", BBSO Report # 0154, 1976; to appear in Solar Physics.

APPENDIX C

Scientists at BBSO who contributed to the research reported in this document.

W.M. Adams, research fellow
B.J. LaBonte, graduate student
K.A. Marsh, research fellow
R.L. Moore, senior research fellow
D. Rabin, graduate student
F. Tang, research assistant
H. Zirin, director of BBSO